ENV 4001: ENVIRONMENTAL SYSTEMS ENGINEERING

Fall 2021 University of South Florida
Problem set #8 Civil & Environmental Eng.
Finish by Wednesday, November 24 Prof. J. A. Cunningham

This problem set will not be collected or graded. Your reward for completing this problem set is that it is essential for learning the course material and passing the tests and final exam.

1. Look up *indicators* 3.9.1 and 11.6.2 for the United Nations Sustainable Development Goals. Write down these indicators. Try to memorize them. If you are curious, look up the data or the metadata that go with these indicators. How are we doing worldwide?

2. *This problem is based on a problem written by Prof Lynn Hildemann of Stanford University*. Your environmental engineering firm got a lot of good press for the excellent job you did designing the water treatment plant for Mudville and the wastewater treatment plant (water reclamation facility) for Nastyville. Now everybody wants to hire you. A company that wants to generate its own electricity to run its factory is thinking about building a small (10-megawatt) power plant. Your firm has been hired to determine how the proposed new power plant would affect the air quality downwind of the new facility.

   The plant will burn anthracite coal from Pennsylvania. The heat value of the coal is 13,000 BTU per pound mass. The composition of the coal (by mass) is 78% carbon, 5% hydrogen, 1% nitrogen, 4% sulfur, 6% oxygen, and 6% ash.

   The design division of your engineering firm tells you that the height of the stack on the power plant will be 32 m. The stack diameter will be 0.91 m, the velocity of the flue gas exiting the stack will be 10 m/s, and the temperature of the flue gas upon exit will be 300 °C (573 K). The efficiency of the power plant will be 45%, which means that 45% of the coal's heat value is actually converted to electricity.

   a. Calculate how much coal must be burned to generate 10 MW, assuming a plant efficiency of 45%. Express your answer in units of kg/s. Take good care of your units! (Hint: you can approach this problem as an energy balance! – like a mass balance, but the units are energy/time instead of mass/time. Efficiency of 45% means that 55% of the incoming energy is lost, so you can use that in the "sink" term of your energy balance.)

problem 2 continues →

2. continued

b. Calculate the emission rate of SO_2 from the power plant's stack, in kg/s. Assume 5% of the sulfur in the coal ends up in ash, and the other 95% is emitted as SO_2. Hint: you know the rate at which coal is burned, and you know how much S is in the coal, and you know the stoichiometry $S + O_2 \rightarrow SO_2$. From these you can figure out the emission rate of SO_2.

The company's CEO has his office 1.0 km directly downwind of where the new power plant would be built. Of course his office is on the top floor of his building, 10 m above ground level. He is worried that the concentration of SO_2 at his office will be too high. He has asked you to calculate the SO_2 concentration at his office, for the case of a windy but sunny day, where the sun is shining, the temperature is 20 °C, the wind speed u_0 at 10 m above ground surface is 6 m/s, the barometric pressure is normal, and an inversion exists at 1000 m above the ground. Terrain between the power plant and the CEO's office is smooth.

c. Which stability class will you use for the calculation?

d. What values will you use for σ_y and σ_z?

e. What is the effective stack height? Hint: use u_0 rather than u in your calculation of plume rise. It might introduce a little error but probably not too much.

f. What will be the wind speed u at that effective stack height? Assume that the facility is out in the countryside, so the terrain is rural and flat. Use the table on the next page to help you. (If you are ambitious, you can now re-check your estimate from part (e) to make sure using u_0 rather than u didn't introduce too much error.)

g. Do you need to consider the inversion in your calculation? Demonstrate.

h. Calculate the SO_2 concentration at the CEO's office. Report your answer in parts per billion (ppb) and in $\mu g/m^3$. NOTE: When I did this part of the assignment, I assumed that the ground is perfectly reflective. That is probably the best way to proceed. However, some years, I run out of time in lecture before we can talk about ground effects. If you want to ignore ground effects, that is OK; hopefully your answer will not be too far away from mine.

i. Look up the National Ambient Air Quality Standard (NAAQS) for SO_2. Is it likely to be exceeded at the CEO's office?

j. The CEO decided that, after the power plant is built, he will move his office to ground level to decrease his exposure to SO_2. Compare the SO_2 concentrations at ground level and at 10 m above ground level. Will the CEO significantly decrease his exposure by moving to a new office? NOTE: For this part, accounting for ground effects might actually be important, I think…probably can't ignore ground effects here….

problem 2 continues →

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k. What do you think about the air quality 1.0 km downwind of a small power plant? Would you feel comfortable living there? What if the plant were 1000 MW instead of 10 MW?

Based on your calculations, the CEO was worried about his health, so he decided to put some wet scrubbers on the stack to remove SO_2. These scrubbers spray lime, $Ca(OH)_2$, into the flue gas to react with SO_2 and convert it to gypsum, $CaSO_4 \bullet 2H_2O$. The net chemistry of the reaction is:

$$Ca(OH)_2 + SO_2 + H_2O + 0.5\ O_2 \rightarrow CaSO4 \bullet 2H_2O$$

l. For the proposed 10-MW power plant, how much lime must you purchase every day to run the scrubbers? How much gypsum would you produce? Note that a 10-MW plant is small – just imagine how much lime and gypsum you would have to handle for a 1000-MW plant!

Here is a table to help you correct wind speed as a function of height about ground surface.

Table 6.1 Variation of the wind speed exponent *p* with stability category

Pasquill stability Class	*Exponent p for rough terrain*	*Exponent p for smooth terrain*
A – the most unstable	0.15	0.07
B	0.15	0.07
C	0.20	0.10
D	0.25	0.15
E	0.40	0.35
F – the most stable	0.60	0.55

Source: Tiwary A, Colls J, 2010. *Air Pollution: Measurement, Modelling, and Mitigation*, 3rd ed. Routledge.

3. These are a few "discussion" questions for you to consider. You don't actually have to write up answers for these (because these problem sets are not graded), but I recommend that you think about them, and ask me questions if you have trouble.

   a. Define or describe *primary standards* and *secondary standards* as defined by the Clean Air Act. Compare these to primary and secondary standards for drinking water as defined under the Safe Drinking Water Act. How are they conceptually similar? In what important respect(s) are they different? (…besides the obvious difference that one is for air and one is for water)

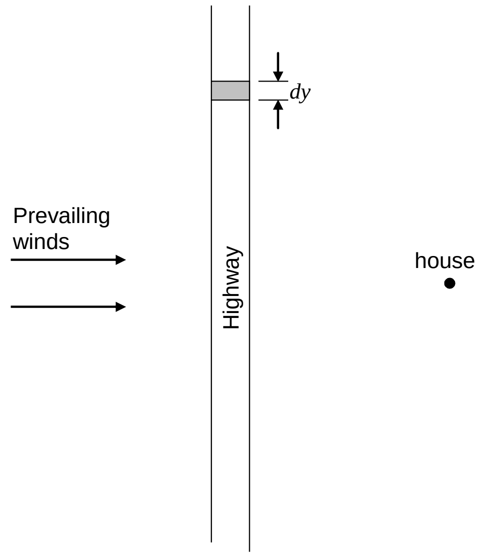
   b. The National Ambient Air Quality Standard for ground-level ozone was modified in 2008 and then again in 2015. What was the pre-2008 standard, what was the 2008–2015 standard, and what is the current (since 2015) standard? Why is the debate over this level controversial? How does it affect the Tampa region and/or other counties in Florida?

   c. Photochemical oxidants (e.g., ozone) are not directly attributable to either people or natural sources. Why, then, are automobiles singled out as the major cause of the formation of ozone?

   d. Explain why the PM2.5 standard is more appropriate than a standard based on total suspended particulates (TSP) for protection of human health.

4. ***<u>Skip in 2021</u>***
   Suppose that you are using an electrostatic precipitator (ESP) to remove fine particulate matter from an air stream at an industrial process. The volumetric flow rate of the air stream is 32 m^3/s, the temperature of the air stream is 25 °C, and the concentration of particulate in the influent air stream is 84 mg/m^3. The plates in your ESP each measure 4 m × 5 m. Under current operation, you are able to remove 90% of the particulate matter from your air stream, but this is deemed insufficient. If you *doubled* the number of plates in your ESP (and also doubled the total electricity supply to the plates, i.e., the power per plate does not change), what would be your new removal efficiency?

5. ***<u>Skip in 2021</u>*** (It's a cool problem, though! – especially if you are a math nerd like me!)
   Based on a problem from <u>Environmental Engineering Science</u> by Nazaroff & Alvarez-Cohen
   Suppose that a busy highway runs north-south for a very long distance, as shown in the figure on the following page. A house is located downwind of the highway, as shown. Cars driving on the road emit carbon monoxide (CO) at a rate $\hat{E}$, which has the following dimensions: mass of CO emitted *per* time *per* length of highway.



Suppose that it is an overcast day with a temperature of 20 °C, and the wind is blowing at an average speed of 2.5 m/sec. There is an atmospheric inversion 1000 m above land surface.

a. Which atmospheric stability class applies to these conditions?
b. If the house is 100 m downwind of the highway, will the presence of the inversion affect the concentration of CO at the house? What if the house is 1000 m downwind of the highway? Hint: find σ_z for each case.
c. What is the rate (in units of mass per time) at which CO is emitted from a small length *dy* of the highway? Hint: this one is really, really simple -- don't make it complicated.
d. Assuming that CO emissions from the highway follow the Gaussian plume model, what is the concentration of CO at the house due to the small section *dy* of the highway? Assume that the house and the highway are both at ground level, and assume perfect reflection of CO when it contacts the ground.
e. Above, you found the concentration at the house due to a small section *dy* of the highway. Now integrate over the length of the highway to find the overall concentration of CO at the house. Hint: you can use this formula, which I got out of my calculus book:

$$\int_0^{\infty} \exp\left(-ay^2\right)dy = \frac{1}{2}\sqrt{\frac{\pi}{a}}$$

f. Suppose that 10,000 vehicles *per* hour drive by the house in each direction. The average speed is 50 miles *per* hour, and the cars emit an average of 20 g CO *per* mile traveled. What is the emissions rate, $\hat{E}$, from the highway? Report your answer in units of g CO *per* meter of highway *per* second.
g. Estimate the concentration of CO at the house if the house is 100 m downwind of the freeway. Also estimate the CO concentration if the house is 1000 m downwind.

h. Look up the National Ambient Air Quality Standard (NAAQS) for CO. Compare the standard to the concentrations you estimated at the house. Would you feel comfortable living in a house that was within 100 m of a busy highway? What about within 1000 m?

6. ***Skip in 2021***

The students in my graduate class (ENV 6519) design several technologies to clean up a site that had been contaminated by trichloroethene (TCE) and cis-dichloroethene (cis-DCE). In one part of the project, the students have to treat an air stream that contains these two contaminants. The air stream is at a temperature of 31 °C and the flow rate is 0.38 m^3/s. Below are some properties of those two chemicals and the air stream:

	Molecular formula	Molecular weight (g/mol)	Henry's constant at 31 °C (dimensionless)	Concentration in air phase (mg/m^3)
TCE	C_2HCl_3	131.39	0.528	40
cis-DCE	$C_2H_2Cl_2$	96.94	0.218	10

a. The students in ENV 6519 treat the air stream with granular activated carbon (GAC), a technology that we did not consider in ENV 4001 this semester. To design the GAC system, the students must convert the contaminant concentrations into partial pressures. Estimate the partial pressure of TCE and cis-DCE in the contaminated air stream. Report your answer in units of Pa.

b. Suppose you wanted to treat the contaminated air stream with a biofilter rather than with GAC. Assume that, in the biofilter, the biodegradation rate of cis-DCE is twice as high as the biodegradation rate of TCE. If you design a biofilter that can treat TCE to an effluent concentration of 5 mg/m^3, what will be the effluent concentration of cis-DCE?

c. Which would you recommend for this stream, GAC or a biofilter? Why?

7. ***Skip in 2021***

a. Answer problem 11.15 in your text book, considering both a low-velocity case and a high-velocity case.

b. Answer problem 11.17 in your text book.